

# Access control lists in password capability environments

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**Abstract** — With reference to a protection system featuring active subjects that attempt to access passive, typed objects, we propose a set of mechanisms supporting the distribution, verification, review and revocation of access privileges. In our approach, a protection domain is a collection of access rights for the protected objects. An access control list is associated with each object to specify the access rights in each protection domain. Objects are grouped into clusters. To access the objects in a given cluster, a subject presents a gate referencing this cluster. The gate is a form of password capability that identifies one or more domains. The gate grants the access rights specified for these domains by the access control lists of the objects in the cluster. A subject that holds a gate and is aimed at distributing the access privileges in this gate in restricted form can reduce the gate to eliminate domains; the gate reduction procedure requires no intervention of the protection system. A small set of protection primitives allows subjects to manage objects and access control lists. Forms of revocation of access permissions are supported at both levels of gates and access control lists.

**Keywords:** access control list; access right; password capability; domain; one-way function; protection.

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## 1 INTRODUCTION

In a classic protection system, a set of active *subjects* (users, processes) attempts to access a set of passive, typed entities called *objects* [16], [29]. The type of a given object states the set of the *operations* that can be executed on this object, and the *access rights* that are necessary to accomplish each operation successfully. A subject aimed at executing a given operation on a given object must possess the access rights required by this operation, as is stated by the object type. A *protection domain* is a collection of access rights for the protected objects. At any given time, each subject is executed in a protection domain, and can take advantage of the access rights included in this domain to operate on the protected objects. In the course of execution, the subject can change domain, according to the access right requirements of the different execution phases.

### 1.1 Capabilities and access control lists

Let  $b_0, b_1, \dots$  be a set of objects, and  $d_0, d_1, \dots$  be a set of protection domain. In a well-

known representation, the state of the protection system takes the form of a matrix, called the *access matrix*, featuring a row for each domain and a column for each object [11], [22]. Element  $AM_{i,j}$  of the access matrix, corresponding to row  $i$  and column  $j$ , contains the specification of the access rights included in domain  $d_i$  for object  $b_j$ . An important aspect is that a domain can also be a protected object, and in this case the domain corresponds to both a row and a column of the access matrix.

The access matrix tends to be large and sparse. Most elements of the access matrix are likely to be empty, so storage in matrix form is usually inadequate. Two alternative, well-known approaches to represent the access matrix are *capability lists* and *access control lists* [24]. In the capability list approach, the access matrix is stored by rows. A capability list is a collection of capabilities, which is associated with each domain, and specifies the access rights included in this domain. A *capability* is a pair  $(b, ar)$ , where  $ar$  specifies a set of access rights for object  $b$  [13]. In the access control list approach, the access matrix is stored by columns. An access control list  $ACL_b$  is associated with each given object  $b$ . Each element of  $ACL_b$  has the form  $(d, ar)$ , and specifies the set  $ar$  of access rights for  $b$  that is included in domain  $d$ .

Capability lists make it easy to determine the access rights that are included in a given domain; however, in a capability environment, it is hard if not impossible to determine the domains that include access rights for a given object (an action of this type requires the inspection of all the capability lists). Conversely, access control lists facilitate the identification of the access rights associated with a given object for each domain; however, in an access control list environment, it is difficult to determine the access rights included in a given domain (an action of this type requires the inspection of all the access control lists).

Capabilities need to be segregated into protected memory regions [5], [14], [28]. This is necessary to prevent a subject that holds a given capability from modifying this capability, e.g. the access right field, to obtain an undue amplification of access rights, or the object identifier field, to forge a capability referencing a different object. In a segmented memory environment, the capability segregation problem can be solved by reserving *ad hoc* memory segments for capability storage, the *capability segments* (in contrast, the *data segments* will be reserved for storage of ordinary information items) [6], [9]. Each capability segment can contain a capability list. Capability segments can only be accessed in a strictly controlled fashion, by executing special machine instructions, the *capability instructions*. In an alternative approach, in a system featuring a form of tagged memory, a one-bit tag can be associated with each memory cell to specify whether this cell contains a capability or an ordinary information item [2], [18], [27]. A cell tagged to contain a capability can be accessed only by using the capability instructions.

*Password capabilities* are an alternative, effective solution to the capability segregation

problem [4], [8], [15], [19]. In a password capability environment, one or more passwords are associated with each protected object. Each password corresponds to a set of access rights for this object. A password capability is a pair  $(b, w)$ , where  $b$  identifies an object, and  $w$  is a password. If  $w$  matches one of the passwords associated with object  $b$ , the password capability grants the corresponding access rights on  $b$ . If passwords are large and sparse, the probability that a malevolent subject guesses a valid password to forge a password capability is vanishingly low [3]. It follows that password capabilities can be mixed in memory with ordinary information items, and can be manipulated by using standard machine instructions.

In this paper, we propose the organization of a protection system that takes advantage of both access control lists, for the protection of ordinary objects, and a form of password capability, called *gate*, for the protection of domains.

## 1.2 Clusters

Objects are grouped into *clusters*. For each object, the cluster includes the corresponding access control list. To access the objects in a given cluster, a subject must demonstrate the right to take advantage of all, or part of, the domains specified by the access control lists in that cluster. This is a problem of certified identity whose solution is the main contribute of this paper, and is based on gates. A gate referencing a given cluster identifies one or more domains in that cluster. A subject that possesses the gate can access the objects in the cluster with the access rights specified for these domains by the access control lists of these objects.

The rest of this paper is organized as follows. Section 2 introduces the gate concept with special reference to the relation existing between a gate for a given cluster and a *base gate* generated when the cluster is created. Gate validation and reduction, to eliminate access permissions, are analyzed in special depth. Section 3 presents a small set of primitives, the *protection primitives*, which allows subjects to access the objects and to manage their access control lists. Section 4 considers the problems related to the review of access permissions, with special reference to gate revocation. Section 5 discusses the motivations for the gate paradigm in reference to a number of important viewpoints, which include fraudulent gate forging, the properties of the proposed form of gate revocation, and gate equivalency. A few considerations concerning performance are presented, in both terms of the memory requirements for gate storage and the execution times for gate validation. Section 6 gives concluding remarks.

## 2 GATES

Let  $C$  be a cluster, and let  $b_0, b_1, \dots$  be the protected objects included in  $C$ . The cluster implements an object protection technique based on domains and access control lists. Let  $d_0, d_1, \dots, d_{n-1}$  be the protection domains for  $b_0, b_1, \dots$ . An access control list  $ACL_b$  is associated with each given object  $b$ . Each element of  $ACL_b$  has the form  $(d, ar)$ , where  $ar$  denotes the set of access rights for  $b$  that is included in domain  $d$ .

A subject  $S$ , aimed at accessing cluster  $C$  to execute operation  $op$  on object  $b$ , must present a gate referencing  $C$ . This gate gives the right to take advantage of one or more domains in  $C$ . The access control list  $ACL_b$  of  $b$  specifies a set of access rights for each of these domains. The access will be accomplished successfully only if the *union* of these sets of access rights includes the access rights that are required to execute  $op$ .

The gate concept is a variant of the classical password capability concept. A gate  $G$  for cluster  $C$  has the form  $G = (W, R)$ . Quantity  $W$  is a password; as will be made clear shortly, this password univocally identifies the cluster. Quantity  $R$ , called the *domain selector*, identifies one or more domains in  $C$ , as follows.  $R$  is partitioned into  $n - 1$  subfields, called *primary selectors* and denoted by  $r$ . Thus,  $R = (r_{n-2}, r_{n-3}, \dots, r_0)$ . The size of a primary selector is  $n$  bits, one bit for each domain (the least significant bit, bit 0, corresponds to the first domain,  $d_0$ ). For each bit that is asserted in a primary selector, the corresponding domain is eliminated from the gate. It follows that the domains referenced by  $G$  are those corresponding to cleared bits in quantity  $r_{n-2} \vee r_{n-3} \vee \dots \vee r_0$ . A primary selector whose value is 0 is called *null*. All null primary selectors are placed in the most significant positions of domain selector  $R$ , at the highest order numbers. In a given gate, if all primary selectors are null,  $R = 0$  and the gate references all the domains in the corresponding cluster. We wish to point out that  $n - 1$  primary selectors allow us to specify any combination of active domains, even if each non-null primary selector has a single bit asserted.

Figure 1 shows two different configurations of domain selector  $R$  of gate  $G = (W, R)$ . In both cases,  $n = 4$ , that is, cluster  $C$  referenced by  $G$  includes four domains, and consequently  $R$  is formed by three primary selectors. Thus we have  $R = (r_2, r_1, r_0)$ . The size of each primary selector is four bits. In the configuration of Figure 1a, bits 0 and 2 of primary selector  $r_0$  are asserted to indicate that domains  $d_0$  and  $d_2$  are lacking from  $G$ . This is similar to the meaning of primary selector  $r_1$  for domain  $d_1$ . The remaining primary selector  $r_2$  is null, so it eliminates no domain. We may conclude that gate  $G$  references a single domain,  $d_3$ . In the configuration of Figure 1b, bits 0, 1 and 2 of primary selector  $r_0$  are asserted to indicate that domains  $d_0, d_1$  and  $d_2$  are excluded from gate  $G$ . The remaining primary selectors  $r_1$  and  $r_2$  are null. In this case, too, the resulting gate  $G$  includes a single domain,  $d_3$ . However, as will be illustrated shortly, the two cases

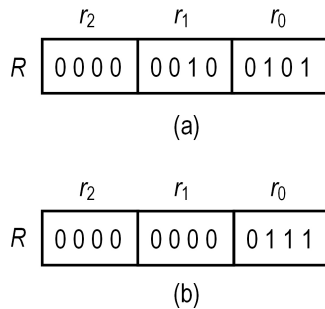


Figure 1: Two different configurations of domain selector  $R$ , corresponding to a single domain,  $d_3$ . In both cases, the cluster is supposed to include four domains. Consequently, the domain selector is partitioned into three primary selectors,  $R = (r_2, r_1, r_0)$ , and the size of each primary selector is four bits.

correspond to different passwords. In fact, in the given cluster we may have several distinct passwords for the same set of domains.

## 2.1 Password derivation

A password, called the *base password*, is associated with each given cluster  $C$  when the cluster is created. This password is denoted by  $BW_C$ . A gate expressed in terms of  $BW_C$  is called the *base gate* and is denoted by  $BG_C$ . In the base gate, the domain selector is always null, thus we have  $BG_C = (BW_C, 0)$ . The base gate references all the domains in cluster  $C$ ; possession of the base gate is equivalent to possession of the access privileges in all these domains.

In gate  $G = (W, R)$ , if one or more primary selectors are non-null,  $R \neq 0$  and the non-null primary selectors identify a password generation path that proceeds from  $BW_C$  to produce password  $W$ . This password generation path is constructed by using a parametric one-way function.

Function  $f$  is *one-way* if given a value  $x$  it is easy to compute  $f(x)$ , and given a value  $y$  it is computationally unfeasible to determine  $x$  such that  $y = f(x)$  [1], [10]. One-way functions can be constructed based on a block cipher to minimize the implementation effort; the block cipher must be adapted to guarantee that the resulting function is not invertible [17], [20]. Function  $g_r(x)$  is a *parametric one-way function* if given a value  $y$  and a parameter  $r$ , it is computationally unfeasible to determine a value  $x$  such that  $y = g_r(x)$  [26]. Thus, a parametric one-way function corresponds to a family of one-way functions, a one-way function for each value of the parameter [23]. Let  $f$  be a one-way function, and let  $E_x(r)$  denote the encryption of  $r$  using symmetric cipher  $E$  with key  $x$ . An example of practical implementation is  $g_r(x) = f(E_x(r))$  [26].

In our protection system, we take advantage of a parametric one-way function, called the *generation function*. This function has the form  $g_r(w)$ , where argument  $w$  is a password

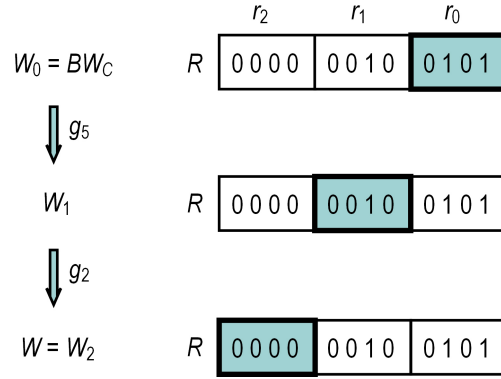


Figure 2: Evaluation of password  $W$  for a specific configuration of domain selector  $R$  of gate  $G = (W, R)$ .

and parameter  $r$  is a primary selector. In gate  $G = (W, R)$ , if  $R \neq 0$  then password  $W$  is produced by a password generation path that starts from base password  $BW_C$  and uses  $g$  iteratively. Let  $R = (r_{n-2}, r_{n-3}, \dots, r_0)$  be the composition of the domain selector. We have  $W_{j+1} = g_{r_j}(W_j)$ ,  $j = 0, 1, \dots, n - 2$ , where  $W_0 = BW_C$  and  $W = W_{n-1}$ . If one or more primary selectors are null, the iterations terminate at the primary selector, say  $r_k$ , that precedes the first null primary selector, and in this case  $W = W_{k+1}$ .

Figure 2 shows the evaluation of password  $W$  for a specific configuration of domain selector  $R$  of gate  $G = (W, R)$ . In this example,  $n = 4$ , that is, cluster  $C$  referenced by  $G$  includes four domains, and consequently  $R$  is formed by three primary selectors. Thus we have  $R = (r_2, r_1, r_0)$ . The size of each primary selector is four bits. If  $R = (0000\ 0010\ 0101)$ , bit 3 is cleared in all the primary selectors. Thus, possession of gate  $G$  allows us to take advantage of the access rights in domain  $d_3$ . In the evaluation of password  $W$ , at the first step we have  $W_0 = BW_C$ . Primary selector  $r_0$  is 0101 (5 in decimal notation), thus we have  $W_1 = g_5(W_0)$ . In the second step, primary selector  $r_1$  is 0010, thus we have  $W_2 = g_2(W_1)$ . Primary selector  $r_2$  is null; this terminates the iterations, and  $W = W_2$ .

## 2.2 Gate validation

Let  $S$  be a subject that possesses gate  $G = (W, R)$ . The gate is valid and it references cluster  $C$  if password  $W$  is derived from base password  $BW_C$  of  $C$ , as has been illustrated in Section 2.1. Subject  $S$  can take advantage of  $G$  to execute operation  $op$  on object  $b$  if the domains of  $C$  specified by  $G$  (as indicated by domain selector  $R$ ) collectively include the access rights required by  $op$ .

In more detail, let  $R = (r_{n-2}, r_{n-3}, \dots, r_0)$ , where each  $r$  denotes a primary selector. If  $W = BW_C$  and  $R = 0$  (that is, all primary selectors are null), then  $G = BG_C$ , and it specifies all the domains of cluster  $C$ . If  $R \neq 0$ , validation of  $G$  proceeds as follows. Parametric generation function  $g$  and the values of the primary selectors are used to

evaluate password  $W$ . We have  $W_0 = BW_C$  and  $W_{j+1} = g_{r_j}(W_j), j = 0, 1, \dots$  etc. The sequence terminates at the primary selector, say  $r_k$ , that precedes the first null primary selector. We define  $W' = W_{k+1} = g_{r_k}(W_k)$ . If no primary selector is null, the sequence terminates at the last primary selector  $r_{n-2}$ , and in this case  $W' = W_{n-1}$ . Gate  $G$  is valid if  $W = W'$ . If  $G$  is valid, we evaluate quantity  $r_{n-2} \vee r_{n-3} \vee \dots \vee r_0$ . The bits of the result that are cleared specify the domains of cluster  $C$  that are actually referenced by  $G$ .

Let  $ACL_b$  denote the access control list of object  $b$ . Let  $ar_{op}$  denote the set of access rights which is required to execute operation  $op$ , as is specified by the type of object  $b$ , and let  $ar_G$  denote the union of the access rights specified by the entries of  $ACL_b$  corresponding to the domains referenced by gate  $G$ . Operation  $op$  can be executed successfully on  $b$  if  $ar_{op} \subseteq ar_G$ . If this is not the case, execution raises an exception of violated protection, and  $op$  terminates with failure.

We wish to remark that our protection system is an extension of the classical access control list paradigm. Suppose that subject  $S$  possesses a gate  $G$  referencing cluster  $C$ . When  $S$  presents  $G$ , if  $G$  specifies a single domain, then the subject enters this domain, as is the case in a traditional access control list environment. If  $G$  specifies two or more domains, then the subject enters a *virtual* domain whose access rights are the *union* of the access rights in the component domains. The gate mechanism allows a subject to change the cluster (and consequently, the virtual domain) dynamically in the course of execution. A subject that holds gates for different clusters can determine the present virtual domain by simply presenting a gate for the corresponding cluster. This is an efficient implementation of the concept of a domain switch in direct subject control.

### 2.3 Gate reduction

A subject  $S_1$  that holds a gate  $G$  referencing domains in a given cluster can transfer a copy of this gate to another subject  $S_2$ . Consequently,  $S_2$  acquires all access permissions granted by  $G$ . Subject  $S_1$  can also transform  $G$  into a new gate  $G'$  for the same cluster and a subset of the domains. This process is called *gate reduction*, and can be especially important to limit the access permissions of the recipient subject  $S_2$ . In fact, gate reduction can be useful even within the boundaries of the same subject, to access a cluster with restricted privileges. This can be convenient to minimize the consequences of misbehaviors due to errors or faults, according to the *principle of least privilege* [21], [25].

Let  $G = (W, R)$  be a gate defined in terms of password  $W$  and domain selector  $R$ , let  $R = (r_{n-2}, r_{n-3}, \dots, r_0)$  be the composition of  $R$  in terms of its primary selectors, and let  $D$  denote the set of the domains referenced by  $G$ , as is specified by the bits that are cleared in quantity  $r_{n-2} \vee r_{n-3} \vee \dots \vee r_0$ . Subject  $S$  that holds  $G$  can reduce this gate into a gate  $G' = (W', R')$  referencing only part of the domains in  $D$ . To this aim, let  $r_k$

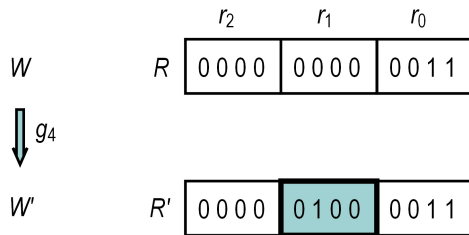


Figure 3: Reduction of gate  $G = (W, R)$ . In this example, the cluster defines four domains, and gate  $G$  references two domains,  $d_2$  and  $d_3$ . After reduction,  $G$  references a single domain,  $d_3$ .

be the first primary selector that is null in  $R$ . We transform  $R$  into  $R'$  by setting the bits of  $r_k$  that correspond to the domains to be eliminated. Afterwards, we generate the new password  $W'$  by using parametric generation function  $g$ . We have  $W' = g_{r_k}(W)$ .

Figure 3 shows the reduction of gate  $G = (W, R)$  in a specific configuration of domain selector  $R$ . In this example,  $n = 4$ , that is, cluster  $C$  referenced by  $G$  includes four domains. Consequently,  $R$  is formed by three primary selectors,  $R = (r_2, r_1, r_0)$ , and the size of each primary selector is four bits. If  $R = (0000\ 0000\ 0011)$ , bits 2 and 3 are cleared in all primary selectors. This means that gate  $G$  references domains  $d_2$  and  $d_3$ . Gate  $G$  can be reduced to reference a single domain, say domain  $d_3$ . To this aim, we modify the least significant null primary selector,  $r_1$ , by setting bit 2 to indicate that domain  $d_2$  is no longer referenced by the gate; the resulting configuration will be  $R' = (0000\ 0100\ 0011)$ . The new password  $W'$  will be obtained by applying parametric generation function  $g$  using primary selector  $r_1$  as a parameter. In decimal notation, the value of this primary selector is 4, so we have  $W' = g_4(W)$ .

### 3 THE PROTECTION PRIMITIVES

The protection system defines a set of primitives, the *protection primitives*, aimed at the management of objects and access control lists (Table 1). This section illustrates the effects of the execution of each of these primitives from the point of view of the subject that issues the primitive. We shall hypothesize that all object types include access rights *own* and *copy*. Access right *own* for a given object makes it possible to delete the object; this access right may also grant other type-specific prerogatives. Access right *copy* makes it possible to create an object copy. Let  $ACL_b$  denote the access control list of object  $b$ . To simplify the presentation, we shall say that a given gate  $G$  includes access right  $ar$  for  $b$  if at least one element of  $ACL_b$  includes  $ar$ , and  $G$  specifies the domain  $d$  of this element.

#### 3.1 Allocating and deleting objects

A cluster is itself an object. In every given cluster, domain  $d_0$  is called the *owner domain* and



Table 1: The protection primitives.

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$b \leftarrow \text{newObject}(G, d)$	Allocates a new object in the cluster referenced by gate $G$ , and returns the name $b$ of this object. The access control list $ACL_b$ of $b$ contains a single element, which includes full access rights for $b$ in domain $d$ . Requires that $G$ references both $d$ and the owner domain $d_0$ .
$\text{deleteObject}(G, b)$	Deletes object $b$ from the cluster referenced by gate $G$ . Requires that $G$ includes access right <i>own</i> for $b$ .
$res \leftarrow \text{operation}(G, b, op)$	In the cluster referenced by gate $G$ , executes operation $op$ on object $b$ , and returns the result of this operation. Requires that $G$ includes the access rights for $b$ that are required by $op$ .
$b' \leftarrow \text{copyObject}(G, b)$	In the cluster referenced by gate $G$ , creates a copy of object $b$ and returns the name $b'$ of the copy. Requires that $G$ includes access right <i>copy</i> for $b$ .
$\text{addAr}(G, d, b, ar)$	In the cluster referenced by gate $G$ , adds access right $ar$ to the element reserved for domain $d$ in the access control list $ACL_b$ of object $b$ . Requires that $G$ includes access right $ar$ for $b$ .
$\text{removeAr}(G, d, b, ar)$	In the cluster referenced by gate $G$ , removes access right $ar$ from the element reserved for domain $d$ in the access control list $ACL_b$ of object $b$ . Requires that $G$ includes access right <i>own</i> for $b$ .

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includes the *own* access right for this cluster. A subject that possesses a gate encompassing domain  $d_0$  is called the *cluster owner*; it can take advantage of the *own* access right to allocate new objects in the cluster, and to delete the cluster. (The cluster owner is also allowed to change the base password; this issue will be considered in subsequent Section 4.)

Object allocation is made possible by the  $b \leftarrow \text{newObject}(G, d)$  protection primitive. Let  $C$  be the cluster referenced by gate  $G$ . Execution of this primitive allocates a new object  $b$  in  $C$ . An access control list  $ACL_b$  is created for  $b$ .  $ACL_b$  contains a single element having the form  $(d, ar_{T_b})$ , where  $ar_{T_b}$  denotes full access rights for object  $b$ , as stated by the type  $T_b$  of  $b$ . Execution terminates successfully only if gate  $G$  references both domain  $d$  and the owner domain  $d_0$  (that is, the subject that executes this primitive must be the owner of cluster  $C$ ).

Object deletion is supported by the  $\text{deleteObject}(G, b)$  primitive. Execution of this primitive deletes object  $b$  from the cluster referenced by gate  $G$ . Execution terminates successfully only if  $G$  includes access right *own* for  $b$  (that is, at least one element of  $ACL_b$  includes access right *own*, and  $G$  specifies the domain  $d$  of this element).

### 3.2 Accessing an object, and creating an object copy

Let  $T_b$  be the type of object  $b$  of cluster  $C$ , and let  $op$  be the generic operation defined by  $T_b$ . Execution of  $op$  on object  $b$  is made possible by protection primitive  $res \leftarrow \text{operation}(G, b, op)$ . Argument  $G$  is a gate referencing  $C$ . Execution of this primitive returns the result  $res$  of  $op$ . Let  $ar$  denote the set of access rights required by  $op$ .

Execution terminates successfully only if  $G$  includes access rights  $ar$  for  $b$ .

Creation of a copy of a given object in cluster  $C$  is made possible by protection primitive  $b' \leftarrow copyObject(G, b)$ . Argument  $G$  is a gate referencing  $C$ . Execution of this primitive allocates a new object  $b'$  in  $C$ ; the value of  $b'$  will be equal to the value of  $b$ . Execution terminates successfully only if  $G$  includes access right  $copy$  for  $b$ .

### 3.3 Adding and revoking access rights

Access control list modifications are made possible by two protection primitives called  $addAr$  and  $removeAr$ . Let  $G$  be a gate referencing cluster  $C$ , let  $b$  be an object in this cluster, and let  $ACL_b$  be its access control list. Primitive  $addAr(G, d, b, ar)$  accesses the element of  $ACL_b$  reserved for domain  $d$  to add the access right specified by argument  $ar$ . Execution of this primitive terminates successfully only if gate  $G$  includes access right  $ar$  for  $b$ . This means that a subject can grant an access right for a given object only if it possesses a gate including this access right.

Primitive  $removeAr(G, d, b, ar)$  accesses the element of  $ACL_b$  reserved for domain  $d$  to eliminate the access right specified by argument  $ar$ . Execution of this primitive terminates successfully only if gate  $G$  includes access right  $own$  for  $b$ . This means that the owner of a given object is the only subject allowed to remove access rights for this object.

## 4 GATE REVOCATION

As seen in Section 2.3, a subject that holds a gate for a given cluster can transfer this gate, possibly in reduced form, to a second subject, which is consequently authorized to access the cluster to take advantage of the domains referenced by the gate. In turn, the second subject can transmit the gate further. It follows that access permissions tend to spread throughout the system. The gate revocation problem consists of giving the owner of a given cluster the ability to review and revoke the gates referencing this cluster. A requirement is that the effects of revocation should extend system-wide.

Our system supports gate revocation through the base password and domain naming. We take advantage of the fact that a cluster is itself an object. As seen in Section 3.1, in each cluster, domain  $d_0$  includes the  $own$  access right for the cluster. The cluster owner, which possesses a gate encompassing domain  $d_0$ , can take advantage of the  $own$  access right to change the base password of that cluster.

Let  $G = (W, R)$  be a gate referencing cluster  $C$ , let  $R = (r_{n-2}, r_{n-3}, \dots, r_0)$  be the composition of the domain selector in terms of its primary selectors, and let  $BW_C$  be the base password of  $C$ . As seen in Section 2.2, when a subject presents  $G$  to access  $C$ , the validity of the gate is verified by an iterative procedure, which starts from  $BW_C$  to

determine a value  $W'$ . The iterations use parametric generation function  $g$  and involve the primary selectors. Gate  $G$  is valid if  $W'$  matches password  $W$  specified by  $G$ . Now suppose that the cluster owner changes base password  $BW_C$ , and let  $BW'_C$  be the new base password. So doing, the cluster owner revokes the validity of base gate  $BG_C = (BW_C, 0)$  and of all the gates derived from  $BG_C$  by reduction. This means that it will no longer be possible to use these gates to reference the domains of  $C$ . The cluster owner possesses the new base gate,  $BG'_C = (BW'_C, 0)$ , and can carry out a new distribution of access rights in the form of gates derived from  $BG'_C$  by reduction.

It is even possible to associate multiple base passwords with the same given cluster. Let  $BW_{C,0}$  and  $BW_{C,1}$  be two base passwords for cluster  $C$ , for instance. The corresponding base gates are  $BG_{C,0} = (BW_{C,0}, 0)$  and  $BG_{C,1} = (BW_{C,1}, 0)$ . The cluster owner is in the position to use these base gates to generate new gates by reduction. Let  $G$  be a gate generated in this way. When  $G$  is validated, the result  $W'$  of the iterative validation procedure of Section 2.2 is compared with both  $BW_{C,0}$  and  $BW_{C,1}$ . If a match is found,  $G$  is valid. In a situation of this type, the cluster owner can revoke the gates for the cluster selectively, simply by eliminating a base password. For instance, by eliminating  $BW_{C,1}$ , the cluster owner revokes the validity of base gate  $BG_{C,1}$  and of all the gates derived from this base gate by reduction. Of course, validity of  $BG_{C,0}$  and its derived gates is not affected by the revocation. These considerations can be extended to an arbitrary number of base gates.

The gate revocation procedure, illustrated above, is valid at gate level and applies to all domains. It is even possible to restrict revocation to a single domain, as follows. In cluster  $C$ , we associate two different names, say  $d'$  and  $d''$ , with a given domain  $d$ . By doing so, we can have different gates referencing  $d$ , which use different domain names. The cluster owner can eliminate a domain name, e.g.  $d''$ . An action of this type produces a selective gate revocation involving all the gates for cluster  $C$  that reference domain  $d$  using name  $d''$ .

## 5 DISCUSSION

### 5.1 Forging gates

Let us suppose that subject  $S$  is fraudulently aimed at forging the base gate of cluster  $C$  from scratch. This base gate has the form  $BG_C = (BW_C, 0)$ , where  $BW_C$  is the base password of  $C$ , and the domain selector is set to 0 to reference all domains. Subject  $S$  does not hold  $BW_C$ , and consequently, it will use a password chosen at random. If base passwords are large and sparse, the probability of a casual match is vanishingly low, and the gate-forging attempt is destined to fail. Similar considerations can be made for a gate

that is not the base gate.

Let us now consider a subject  $S$  that possesses a gate  $G = (W, R)$  referencing a set of domains in cluster  $C$ . Suppose that  $S$  is aimed at transforming  $G$  into a new, stronger gate  $G' = (W', R')$ . To this aim,  $S$  modifies domain selector  $R$  to form the new domain selector  $R'$  referencing more domains. A result of this type can be simply obtained by clearing the most significant primary selector that is non-null in  $R$ . The next step is to derive password  $W'$  from password  $W$ . In fact,  $W'$  *precedes*  $W$  in the iterative generation procedure, illustrated in Section 2.1, which starts from base password  $BW_C$  of cluster  $C$  to produce  $W$ . But parametric generation function  $g$ , used to generate  $W$  from  $W'$ , is one-way. This means that it is computationally unfeasible to invert  $g$  to obtain  $W'$  from  $W$ . In this case, too, subject  $S$  will have to use a random  $W'$ , and the probability of success is virtually null.

## 5.2 Gate revocation

As seen in Section 1, gates are forms of capabilities. The access right revocation problem is common in capability environments [15]. Several solutions have been proposed to this problem. A propagation graph can be constructed for each capability, which keeps track of all copies of this capability existing throughout the system [7]. This solution tends to subvert one of the main advantages of the capability model, i.e. simplicity in the transmission of access permissions between subjects. We can limit the capability lifetime, and in this case the validity of capabilities must be renewed at regular intervals [12]. This solution tends to overburden the protection system with explicit requests to extend the capability lifetime.

In a different approach, as seen in Section 4, our system supports gate revocation through the base passwords. In a given cluster, if we delete a base password, we revoke the base gate defined in terms of this base password, and also all the gates derived from this base gate by reduction. In spite of its simplicity, this gate revocation mechanism possesses a number of interesting properties. Revocation is [7]:

- *selective*, that is, it can be limited to a subset of the subjects that possess a gate for the given cluster, if this subset has been associated with a specific base password and we eliminate this base password;
- *independent*, that is, gates for the same set of domains can be revoked independently of each other, if these gates derive from base gates defined in terms of different base passwords;
- *transitive*, that is, if a gate is revoked, the effects of the revocation propagates to all the subjects that received a copy of this gate, independently of the distribution path followed by the gate copy to reach the corresponding recipient (and in fact, a

copy of a gate is indistinguishable from the original, and gates have no memory of subsequent copy actions);

- *temporal*, and in fact, a revocation obtained by changing a given base password can be reversed through the same mechanism used for revocation, by restoring the original value of that base password.

### 5.3 Equivalent gates

Let  $C$  be a cluster, let  $G = (W, R)$  be a gate, and let  $R = (r_{n-2}, r_{n-3}, \dots, r_0)$  be the composition of the domain selector of this gate in terms of its primary selectors. As seen in Section 2, the set of domains in  $C$  that are referenced by  $G$  is specified by the bits that are cleared in quantity  $r_{n-2} \vee r_{n-3} \vee \dots \vee r_0$ . It follows that different configurations of the primary selectors may well correspond to the same set of domains. The corresponding gates are said to be *equivalent*. For instance, let us consider gates  $G_1 = (W_1, R_1)$  and  $G_2 = (W_2, R_2)$ , where  $R_2$  is obtained by changing the order of the non-null primary selectors in  $R_1$ . In this case,  $G_1$  and  $G_2$  are equivalent, but the iterative password generation procedure will produce different results, so  $W_1 \neq W_2$ .

It is important to note that no additional cost follows from the point of view of the memory requirements for password storage. In fact, a single password needs to be stored for each given cluster, the base password. Password validation is not based on comparison with a pre-existing set of passwords, as is the case in password capability environments [8], [15], [19]. Instead, as seen in Section 2.2, password validation is the result of a dynamic evaluation procedure, which starts at the base password and terminates at the password to be validated.

### 5.4 Considerations concerning performance

#### 5.4.1 Storage requirements

The memory requirements for storage of a gate are the result of two components, the size of the password and the size of the domain selector. The size of the password is determined by the overall security requirements, e.g. 128 bits. The size of the domain selector is a function of the number of the domains in the corresponding cluster. In fact, as seen in Section 2, for  $n$  domains we have  $n - 1$  primary selectors, and the size of each primary selector is  $n$  bits.

In a possible, effective implementation of a protection system using gates, we shall define a limited number of gate formats. We may have a *short gate* supporting up to four domains ( $n = 4$ ). In this case, the domain selector consists of three primary selectors of four bits each, which fit into two bytes. Then we have a *standard gate* for up to eight

domains ( $n = 8$ ). Here, the domain selector consists of seven primary selectors of eight bits each, for a total of seven bytes. Finally, a *long gate* can support up to 16 domains ( $n = 16$ ). In this case, we have 15 primary selectors of size 16 bits, for a total of 30 bytes. If the size of a password is 128 bits, the memory requirements for storage of a gate are 18 bytes for a short gate, 23 bytes for a standard gate, and 46 bytes for a long gate. (In contrast, for 64-bit object identifiers and 128-bit passwords, the size of a classical password capability is 24 bytes.)

As seen in Section 2, the primary selectors are aimed at specifying domain reductions. If each primary selector eliminates a single domain, we need  $n - 1$  primary selectors to specify all possible reductions. A gate is often reduced before being transmitted to another subject, to limit the access privileges of the recipient. In fact, it is rarely the case that a gate traverses a number of transmission steps, with reduction, as high as is made possible, for instance, by the long gate format. This suggests us to limit the number of possible reductions to save storage. With a limit of eight reductions, the long gate format features eight primary selectors of size 16 bits, and overall the size of the domain selector is 16 bytes. A subject that has to apply a further reduction when no null primary selector is available will ask the cluster owner to *shrink* the gate, that is, to produce an equivalent gate with a single non-null primary selector. In this primary selector, the cluster owner will set each bit that is asserted in at least one primary selector in the original gate. The password of the equivalent gate will be recalculated starting from the base password, as usual.

#### 5.4.2 Execution times

As seen in Section 2.2, validation of a given gate is an iterative procedure that implies one execution of the parametric generation function  $g$  for each non-null primary selector in that gate. Let  $T_g$  denote the time necessary for a single iteration, including the execution time of  $g$ , and let  $m$  be the number of non-null primary selectors in gate  $G$ , where  $m \leq n - 1$ ,  $n$  is the number of the domains, and  $n - 1$  is the number of the primary selectors. Let  $T_v$  denotes the total time necessary for validation of a gate; we have  $T_v = m \cdot T_g$ . The maximum time cost corresponds to the case of no null component, when  $m = n - 1$  and  $T_{v,max} = (n - 1) \cdot T_g$ . The time cost is lower for one or more null components, and the minimum cost corresponds to the validation of the base gate, when  $m = 0$  and  $T_{v,min} = 0$ .

As seen in Section 5.4.1, it is always possible to shrink a gate featuring two or more non-null primary selectors into an equivalent gate featuring a single non-null primary selector. A positive side effect is a reduction of the gate validation time. After shrinking the gate, we have  $m = 1$  and  $T_v = T_g$ .

## 6 CONCLUDING REMARKS

We have considered an important problem in the design of a protection system, i.e. the definition of the mechanisms supporting the distribution, verification, review and revocation of access permissions. We have proposed the organization of a protection system that takes advantage of both access control lists, for the protection of ordinary objects, and a new form of password capability, the gate, for the protection of domains. In our approach:

- Ordinary objects are grouped into clusters. In a cluster, an access control list is associated with each object. The access control list specifies the access rights for this object that are included in each protection domain.
- A subject can access the objects in a given cluster only if it possesses a gate for this cluster. The gate is a form of password capability, extended to contain a domain selector that identifies one or more domains. A relation exists between the password in a given gate and a base password associated with the cluster when the cluster is created. This relation is expressed in terms of the domain selector, by application of a parametric one-way generation function.
- A gate for a given cluster identifies a virtual protection domain in terms of the domains of that cluster. The access rights in the virtual domain are the union of the access rights in the component domains.
- A small set of protection primitives allows subjects to manage objects and access control lists.

We have obtained the following results:

- A subject that holds a gate for a given cluster can generate a new gate for this cluster, to restrict the gate extent by eliminating domains. The gate reduction procedure can be iterated to eliminate more domains. Gate reduction is usually aimed at distributing restricted access privileges to another subject, but can be also used within the boundaries of the same subject, to access a cluster with less privileges to minimize the consequences of errors or faults. Subjects can carry out gate reduction autonomously; no intervention of the protection system is required.
- The duality of gates and access control lists allows us to carry out orthogonal forms of review and revocation of access privileges. A change of the access privileges in a given access control list affects only the gates referencing the domains involved in the change. On the other hand, the owner of a given cluster can replace the base password of that cluster; as a consequence, validity of all the gates referencing that cluster is revoked. The cluster owner can subsequently grant gates derived from the new password, thereby producing a new distribution of access rights. This gate revocation mechanism results to possess a number of interesting properties;

revocation is selective, independent, transitive and temporal.

- If base passwords are large and sparse, it is impossible for a malevolent subject to forge valid gates from scratch. Transformation of a valid gate into a stronger gate referencing more domains is prevented by the one-way property of the gate generation function.
- A gate can be shrunk into an equivalent gate featuring a single non-null primary selector. So doing, we keep the memory requirement for gate storage low, by reserving less space for the reduction field while not limiting the number of possible reductions. Furthermore, shorter execution times are required for gate validation.

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## REFERENCES

- [1] S. Bakhtiari, R. Safavi-Naini, and J. Pieprzyk. Cryptographic hash functions: a survey. Technical report, Centre for Computer Security Research, Department of Computer Science, University of Wollongong, Australia, 1995.
- [2] N. P. Carter, S. W. Keckler, and W. J. Dally. Hardware support for fast capability-based addressing. *ACM SIGPLAN Notices*, 29(11):319–327, November 1994.
- [3] M. D. Castro, R. D. Pose, and C. Kopp. Password-capabilities and the Walnut kernel. *The Computer Journal*, 51(5):595–607, 2008.
- [4] J. S. Chase, H. M. Levy, E. D. Lazowska, and M. Baker-Harvey. Lightweight shared objects in a 64-bit operating system. *ACM SIGPLAN Notices*, 27(10):397–413, October 1992.
- [5] M. de Vivo, G. O. de Vivo, and L. Gonzalez. A brief essay on capabilities. *ACM SIGPLAN Notices*, 30(7):29–36, July 1995.
- [6] D. M. England. Capability concept mechanism and structure in System 250. In *Proceedings of the International Workshop on Protection in Operating Systems*, pages 63–82, IRIA, Paris, 1974.
- [7] V. D. Gligor. Review and revocation of access privileges distributed through capabilities. *IEEE Transactions on Software Engineering*, SE-5(6):575–586, November 1979.
- [8] G. Heiser, K. Elphinstone, J. Vochteloo, S. Russell, and J. Liedtke. The Mungi single-address-space operating system. *Software – Practice and Experience*, 28(9):901–928, July 1998.
- [9] G. Klein, K. Elphinstone, G. Heiser, J. Andronick, D. Cock, P. Derrin, D. Elkaduwe, K. Engelhardt, R. Kolanski, M. Norrish, et al. seL4: formal verification of an OS kernel. In *Proceedings of the 22nd ACM Symposium on Operating Systems Principles*, pages 207–220, Big Sky, MT, USA, October 2009. ACM.
- [10] L. Lamport. Password authentication with insecure communication. *Communications of the ACM*, 24(11):770–772, November 1981.
- [11] B. W. Lampson. Protection. *ACM SIGOPS Operating Systems Review*, 8(1):18–24, January 1974.



- [12] A. W. Leung and E. L. Miller. Scalable security for large, high performance storage systems. In *Proceedings of the Second ACM Workshop on Storage Security and Survivability*, pages 29–40, Alexandria, Virginia, USA, October 2006. ACM.
- [13] H. M. Levy. *Capability-Based Computer Systems*. Digital Press, Bedford, Mass., 1984.
- [14] L. Lopriore. Encrypted pointers in protection system design. *The Computer Journal*, 55(4):497–507, April 2012.
- [15] L. Lopriore. Password capabilities revisited. *The Computer Journal*, 58(4):782–791, April 2015.
- [16] L. Lopriore. Password management: distribution, review and revocation. *The Computer Journal*, 58(10):2557–2566, October 2015.
- [17] R. C. Merkle. One way hash functions and DES. In *Proceedings of the 9th Annual International Cryptology Conference – Advances in Cryptology*, pages 428–446, Santa Barbara, California, USA, August 1989. Springer.
- [18] P. G. Neumann and R. J. Feiertag. PSOS revisited. In *Proceedings of the 19th Annual Computer Security Applications Conference*, pages 208–216, Las Vegas, NV, USA, December 2003. IEEE.
- [19] R. Pose. Password-capabilities: their evolution from the Password-Capability System into Walnut and beyond. In *Proceedings of the Sixth Australasian Computer Systems Architecture Conference*, pages 105–113, Gold Coast, Australia, January 2001. IEEE.
- [20] B. Preneel, R. Govaerts, and J. Vandewalle. Hash functions based on block ciphers: a synthetic approach. In *Proceedings of the 13th Annual International Cryptology Conference*, pages 368–378, Santa Barbara, California, USA, August 1993. Springer.
- [21] J. H. Saltzer and M. D. Schroeder. The protection of information in computer systems. *Proceedings of the IEEE*, 63(9):1278–1308, September 1975.
- [22] P. Samarati and S. De Capitani Di Vimercati. Access control: policies, models, and mechanisms. In R. Focardi and R. Gorrieri, editors, *Foundations of Security Analysis and Design*, pages 137–196. Springer, Berlin, Heidelberg, 2001.
- [23] R. S. Sandhu. Cryptographic implementation of a tree hierarchy for access control. *Information Processing Letters*, 27(2):95–98, 1988.
- [24] R. S. Sandhu and P. Samarati. Access control: principles and practice. *IEEE Communications Magazine*, 32(9):40–48, September 1994.
- [25] F. B. Schneider. Least privilege and more. *IEEE Security & Privacy*, 1(5):55–59, September 2003.
- [26] W. Trappe, J. Song, R. Poovendran, and K. J. Liu. Key management and distribution for secure multimedia multicast. *IEEE Transactions on Multimedia*, 5(4):544–557, 2003.
- [27] R. N. Watson, J. Woodruff, P. G. Neumann, S. W. Moore, J. Anderson, D. Chisnall, et al. Cheri: a hybrid capability-system architecture for scalable software compartmentalization. In *Proceedings of the IEEE Symposium on Security and Privacy*, San Jose, California, USA, May 2015.
- [28] M. V. Wilkes. Hardware support for memory protection: capability implementations. *ACM SIGARCH Computer Architecture News*, 10(2):107–116, March 1982.
- [29] X. Zhang, Y. Li, and D. Nalla. An attribute-based access matrix model. In *Proceedings of the 2005 ACM Symposium on Applied Computing*, pages 359–363, Santa Fe, New Mexico, USA, March 2005. ACM.